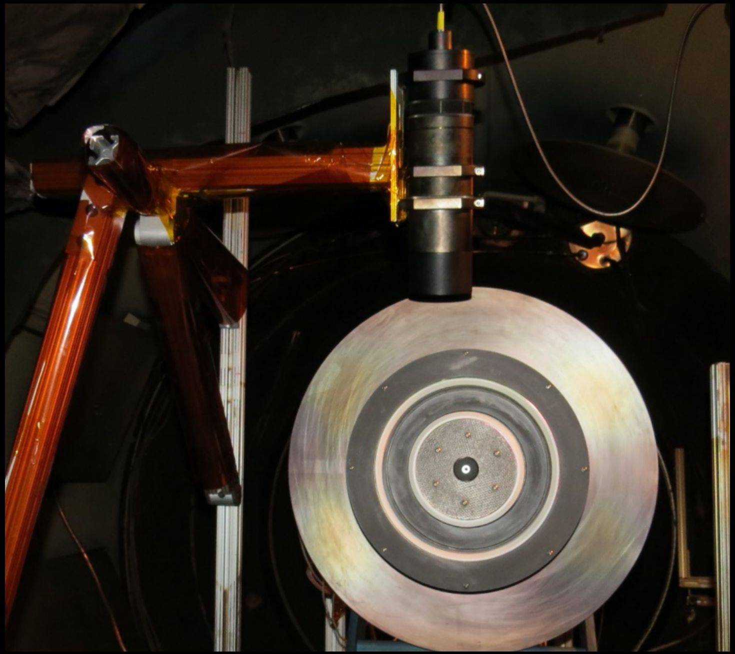
Spatiotemporally Resolved Ion Velocity Distribution Measurements in the 12.5 kW HERMeS Hall Thruster



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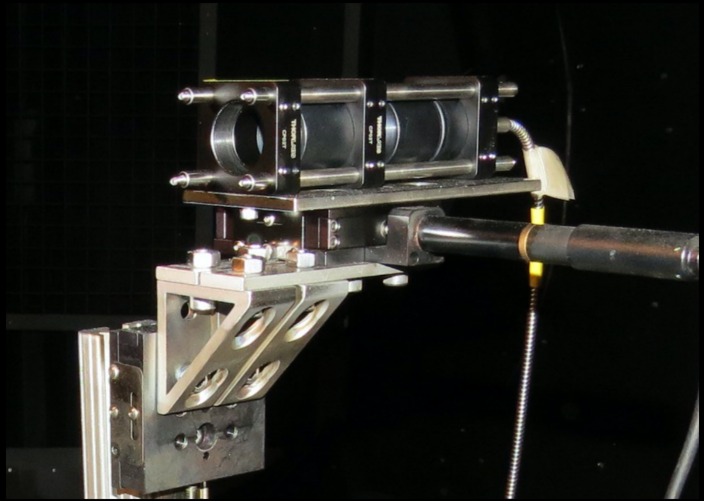


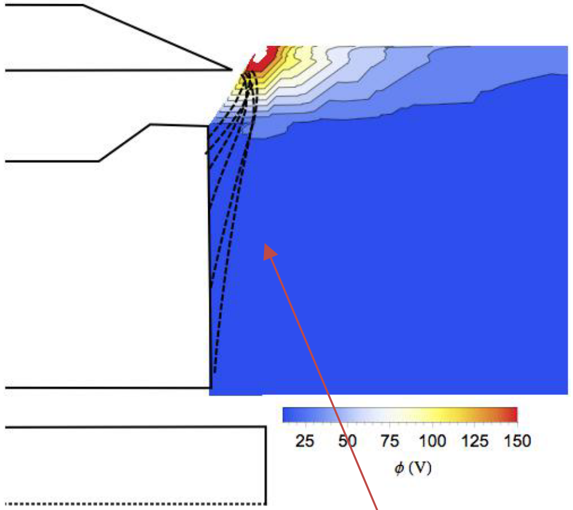
60th Annual Meeting of the APS Division of Plasma Physics
Oregon Convention Center • Portland, OR
November 5 – 9, 2018

Introduction

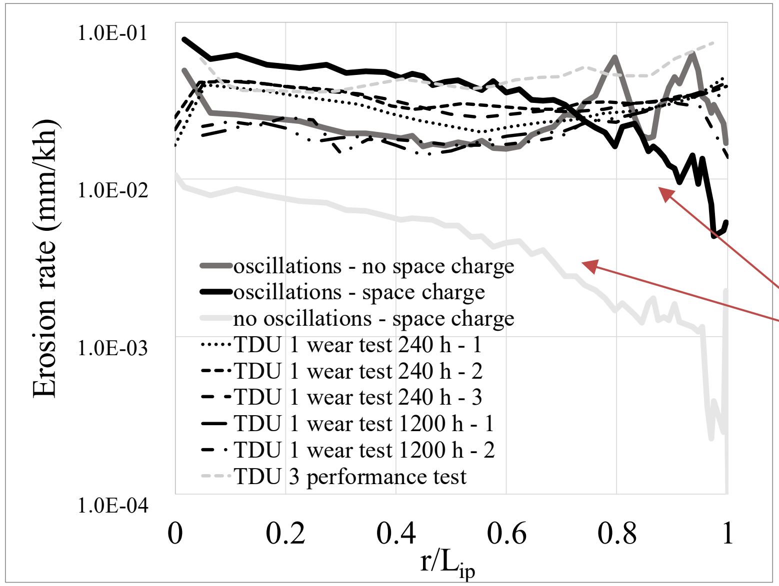
- NASA's 12.5 kW Hall Effect Rocket with Magnetic Shielding (HERMeS) will be qualified for flight through a combination of laboratory wear tests and physics-based modeling using the Hall2De code.
- Non-invasive measurements of the ion velocity distribution function (IVDF) using laser-induced fluorescence (LIF) are a critical component of the life qualification plan:
  - LIF provides the empirical inputs necessary to set the anomalous cross-field transport profile in the Hall2De simulations.
  - Detailed measurements of ion velocities as a function of position can be used to validate the code and better understand the mechanisms behind measured surface erosion rates.
  - Probe measurements in the discharge channel perturb the plasma to an unacceptable extent and therefore cannot be used for these studies (Jorns et al., AIAA-2015-4006).
- Over the long (>>10 kHr) service life enabled by magnetic shielding, front pole erosion can be an important life-limiting mechanism. LIF measurements seek to build understanding and support modeling of the erosion processes.

Motivation

- Ions causing pole erosion likely originate from the edges of the main ion beam (Jorns et al., AIAA-2016-4839).
- Simulations have demonstrated that the erosion rate depends strongly on the acceleration region location and the shape of beam-edge potential contours (Lopez Ortega et al., IEPC-2017-154).
- Discharge oscillations with movement of the acceleration zone can dramatically increase pole erosion (Lopez Ortega et al., IEPC-2017-154).
- Simulations have successfully modeled HERMeS pole erosion at 500 – 600 V, 20.8 A, but have thus far under-predicted erosion at 300 V, 20.8 A. LIF can help uncover the missing physics.



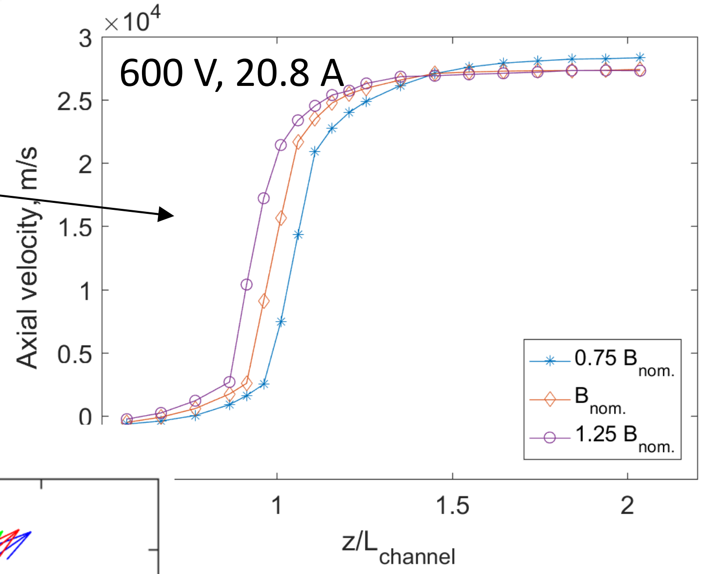
Ion trajectories from the beam edge to the inner pole of an MS thruster (Jorns et al., AIAA-2016-4839)



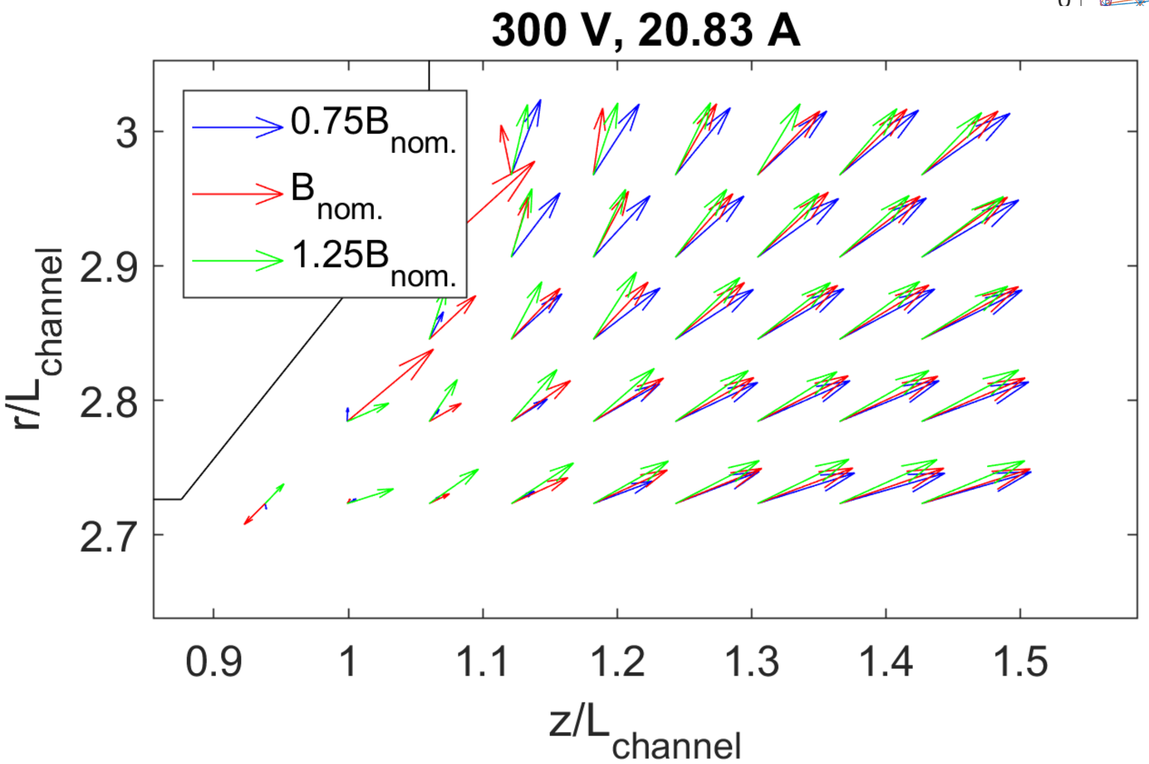
Simulated HERMeS inner pole erosion at 600 V, 20.8 A, with and without oscillations in the acceleration zone position (Lopez Ortega et al., IEPC-2017-154)

Beam Edge Ion Velocities

- HERMeS inner pole erosion increases at higher magnetic field strengths (Frieman et al., AIAA-2018-4645; Williams et al., IEPC-2017-207), even though LIF along the channel centerline shows that the acceleration zone is further upstream at higher B.
  - Contrary to expectations that moving the acceleration zone downstream should expose the pole covers to more beam ions.

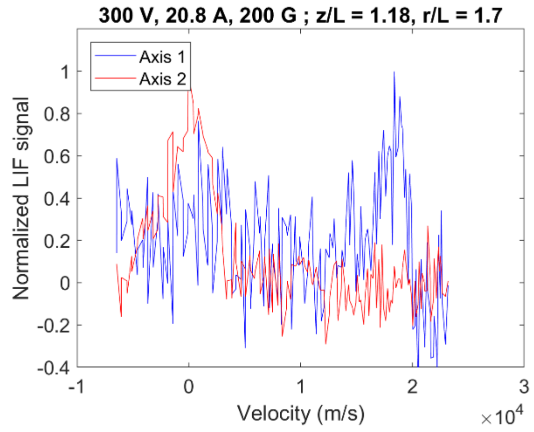


- High-resolution LIF vector maps show that ion trajectory divergence increases at higher magnetic fields
  - Velocities of fast ions born in the channel near the anode potential can be used to estimate potential contours.

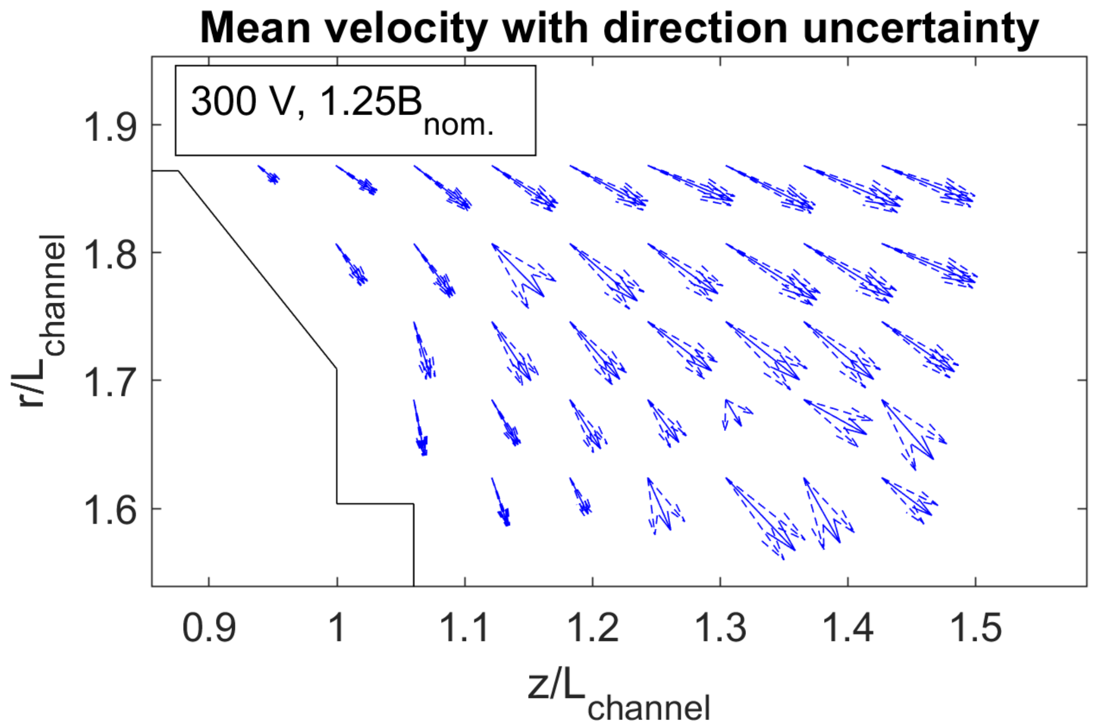


Uncertainty Analysis: Bootstrap Resampling

- Some beam-edge LIF profiles are very noisy due to the low plasma density in these regions. It's important to quantify the error in the mean velocity.



- Chosen approach: **bootstrap resampling** (B. Efron, *Annals Stat., 7, 1, 1979)*
  - Commonly used in space physics for calculating uncertainties in moments of velocity distributions from particle detectors.
  - Randomly sample from the data *with replacement* to create a new bootstrap data set. Calculate the first moment for many (~10,000) bootstrap data sets—the variance in the bootstrap mean velocity approximates the variance in the mean calculated from the raw data.
- Standard error propagation techniques are used to calculate uncertainty in velocity vector angles.

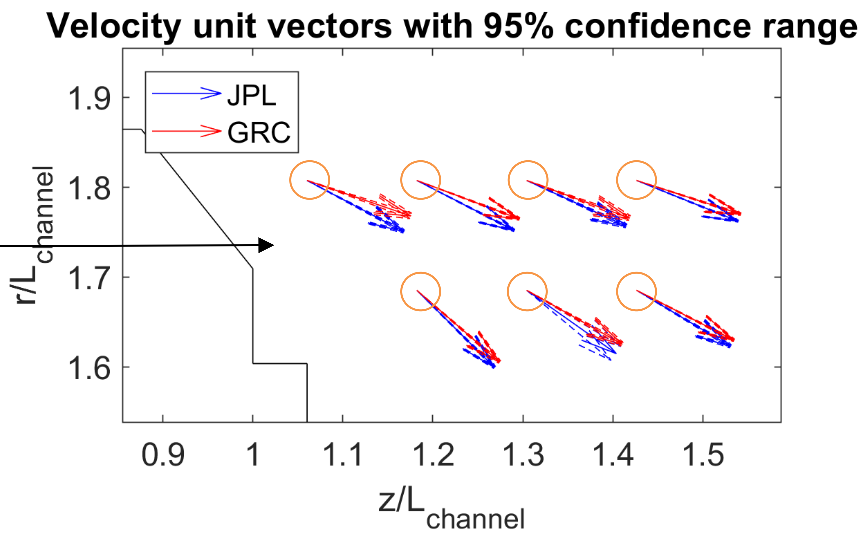


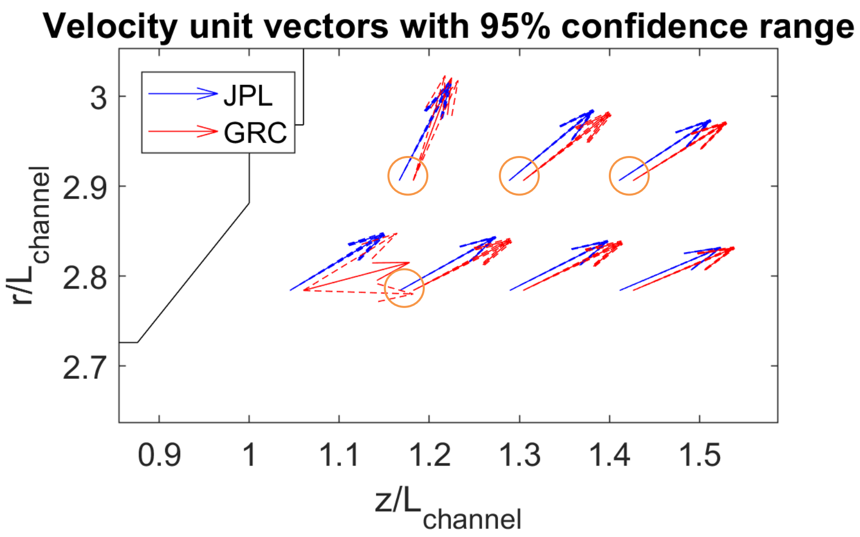
Variation Across Thrusters and Facilities

- Measured pole erosion rates in HERMeS Technology Demonstration Units (TDUs) have varied by >2x across different facilities and TDU units, and as a function of time within a given wear test.
- These erosion variations may arise due to small changes in beam edge plasma properties.

Comparison of LIF data taken at NASA GRC on HERMeS TDU-1 and at NASA JPL on HERMeS TDU-2:

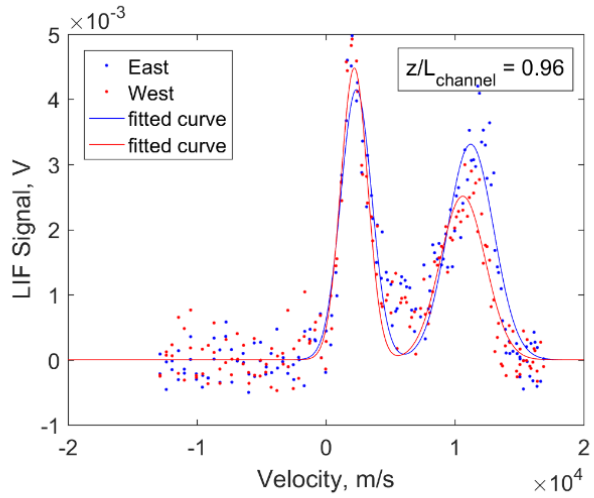
- Dashed arrows show 95% confidence interval for unit vector directions.
- Circled points have a statistically significant difference between the datasets.

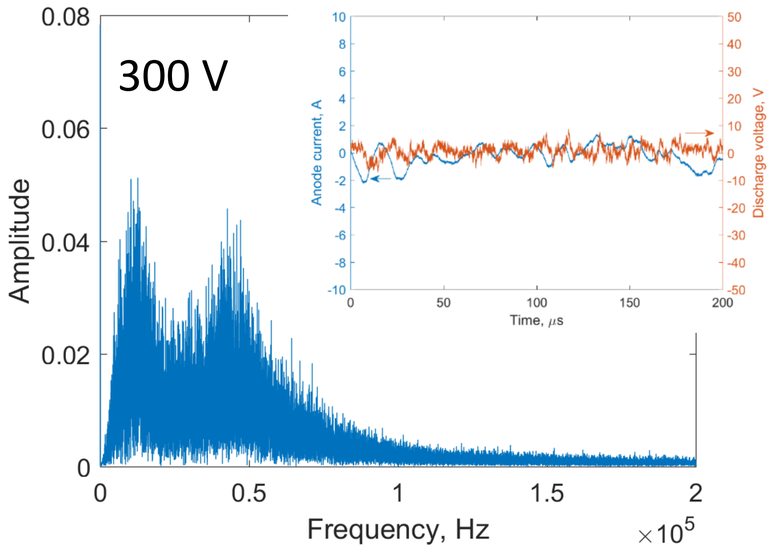


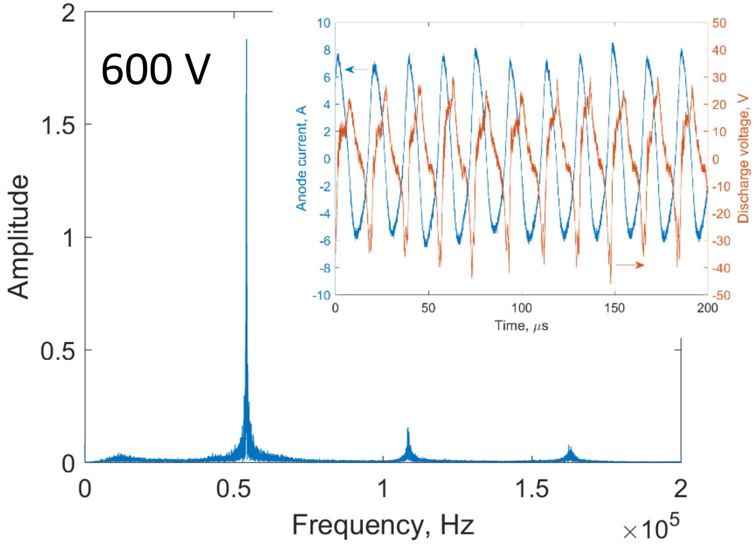


Motivation for Time-Resolved LIF

- Previously, bi-modal IVDFs on the channel centerline were measured at $V_d \geq 500$ V. These were interpreted as arising from time-averaging over motion of the acceleration zone (Chaplin et al., *J. Appl. Phys.*, in press).
- Given the importance of oscillations for pole erosion, more detailed understanding of the time-dependent behavior was needed.
- HERMeS I_d oscillations are high amplitude with a sharply peaked frequency spectrum at 500 – 600 V but low-amplitude with a broad spectrum at 300 – 400 V.
- A time-resolved LIF technique for HERMeS should ideally be able to handle both types of oscillations.

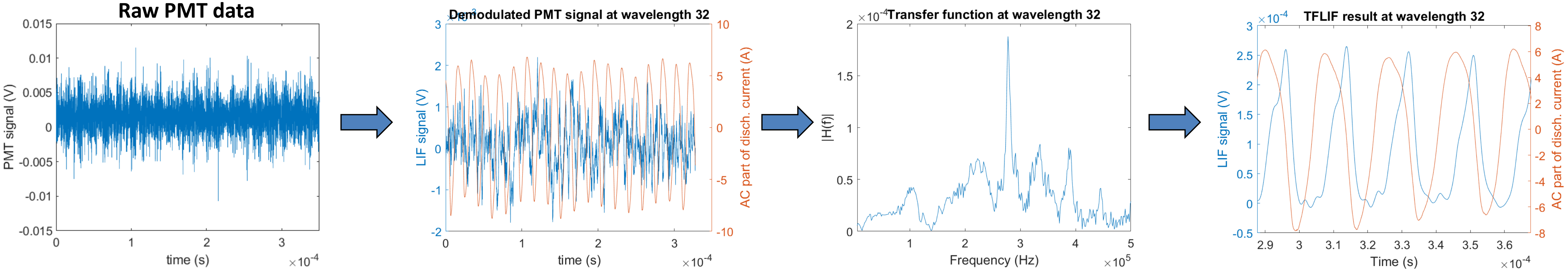




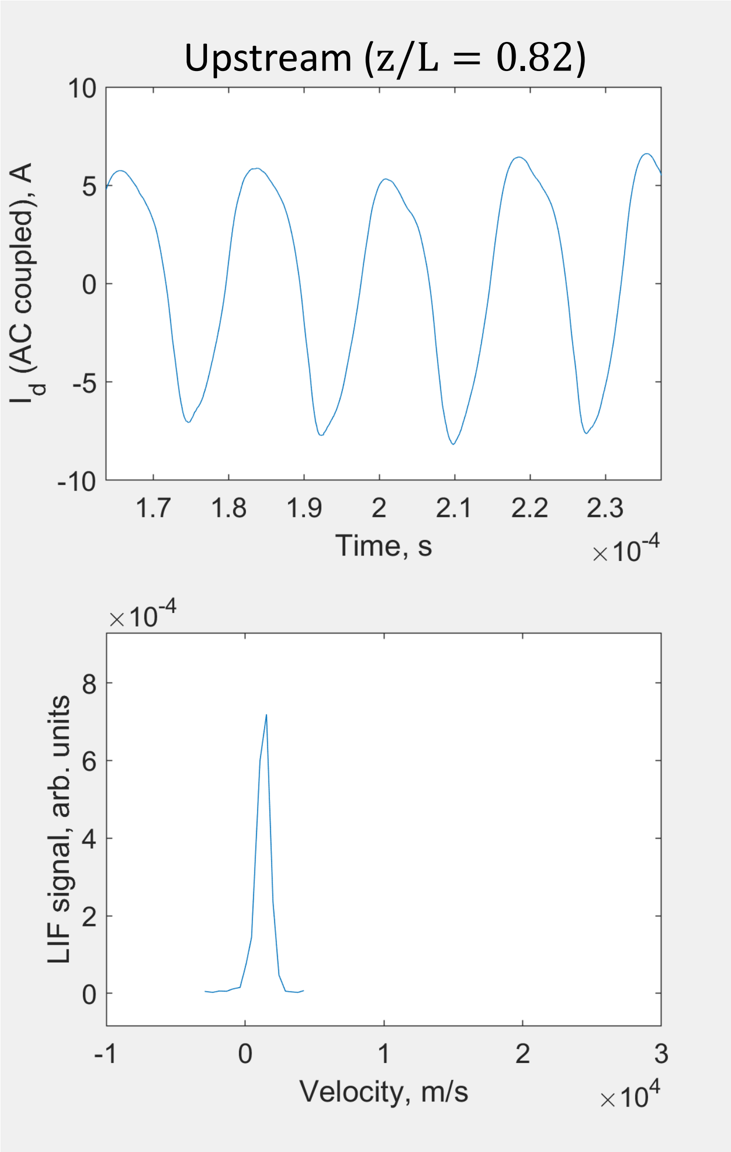


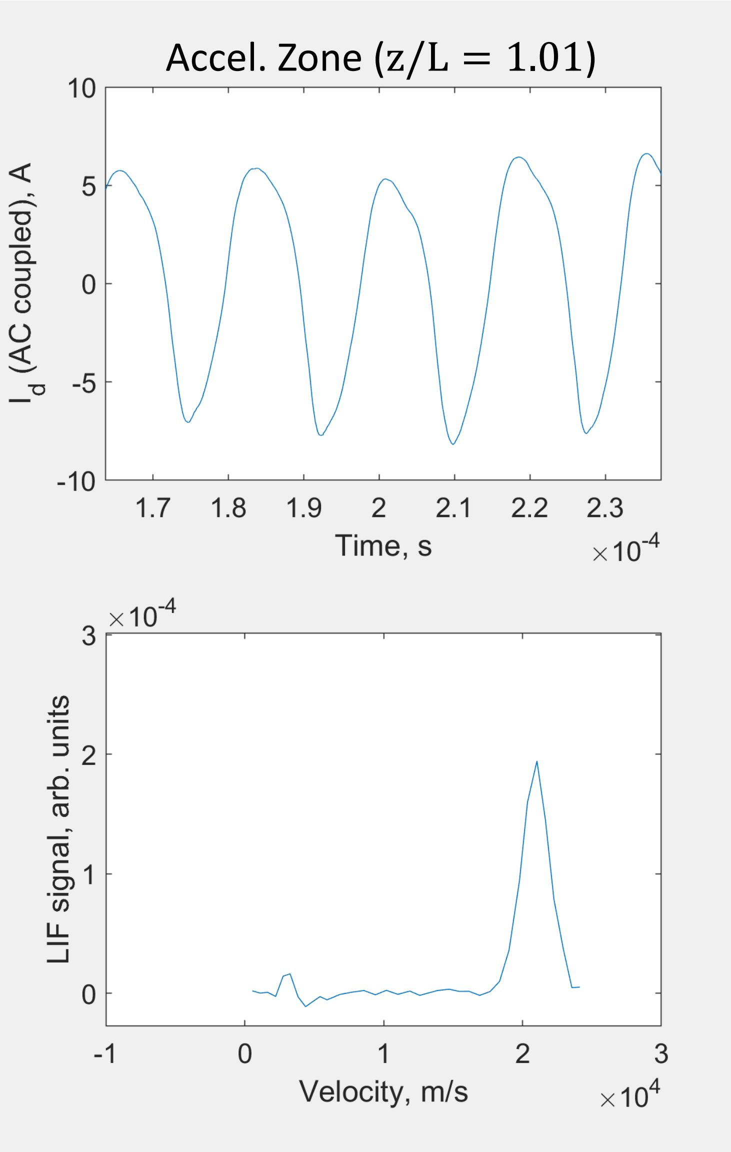
Time-Resolved LIF with Transfer Function Averaging

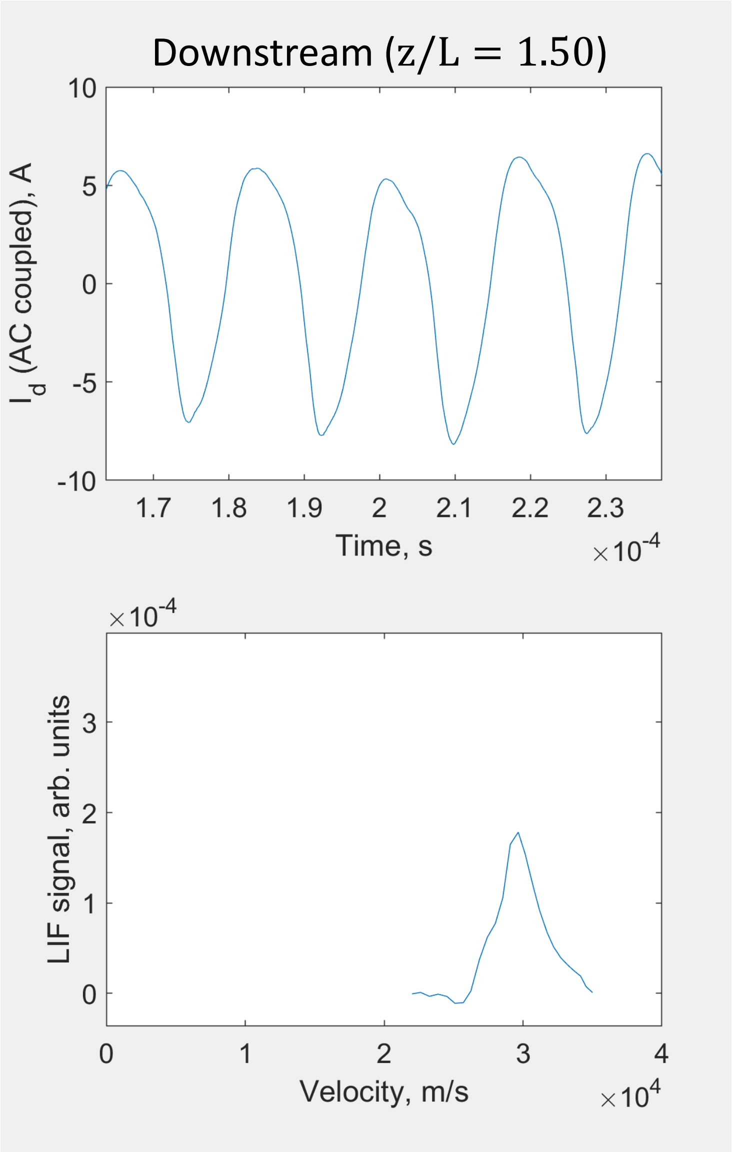
- LIF has intrinsically poor signal-to-noise ratio, so averaging over a long period of time or many data acquisitions is necessary to obtain useful results.
- **Transfer function averaging** enables time-resolved (~100 kHz bandwidth) LIF even with non-periodic oscillations (Durot et al., *RSI*, 85, 013508, 2014 ; Lobbia et al., AIAA-2008-4650).
  - PMT output is digitized at high speed (25 MHz) and lock-in amplification and other data reduction are carried out in post-processing.
  - Method relies on the assumption that a complex-valued function $H(\omega)$ exists that relates the Fourier transform $\hat{l}(\omega)$ of the LIF signal and the Fourier transform $\hat{r}(\omega)$ of some reference signal: $\hat{l}(\omega) = H(\omega)\hat{r}(\omega)$



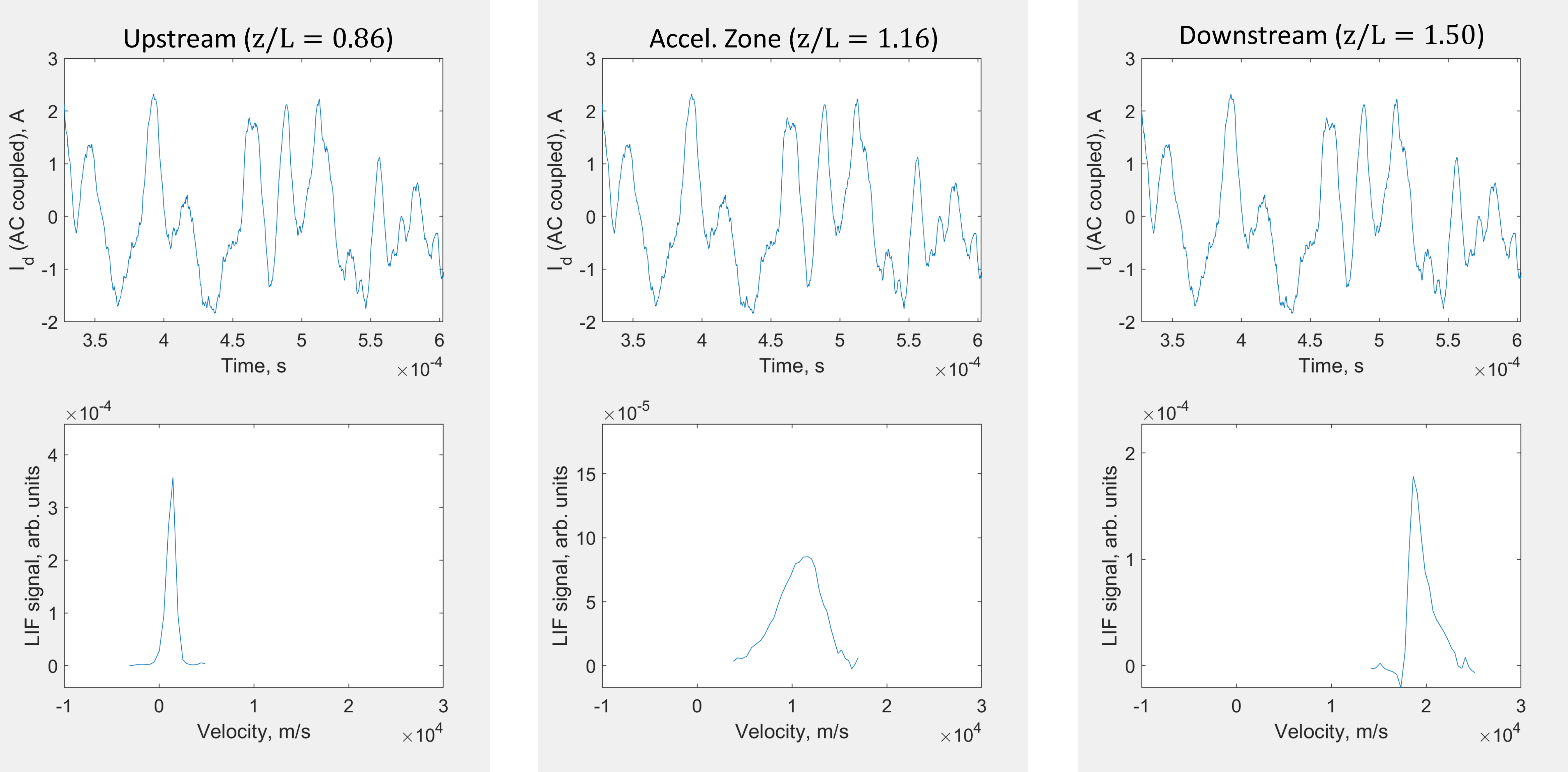
Quasi-Periodic Oscillations – 600 V



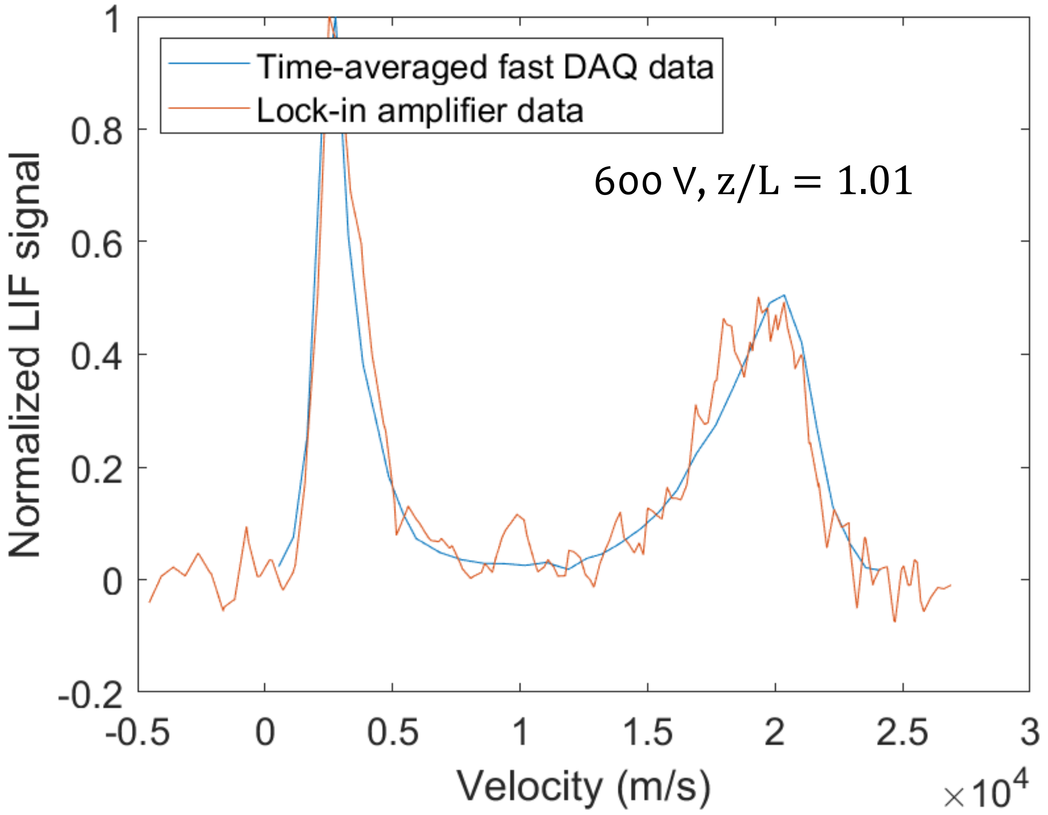




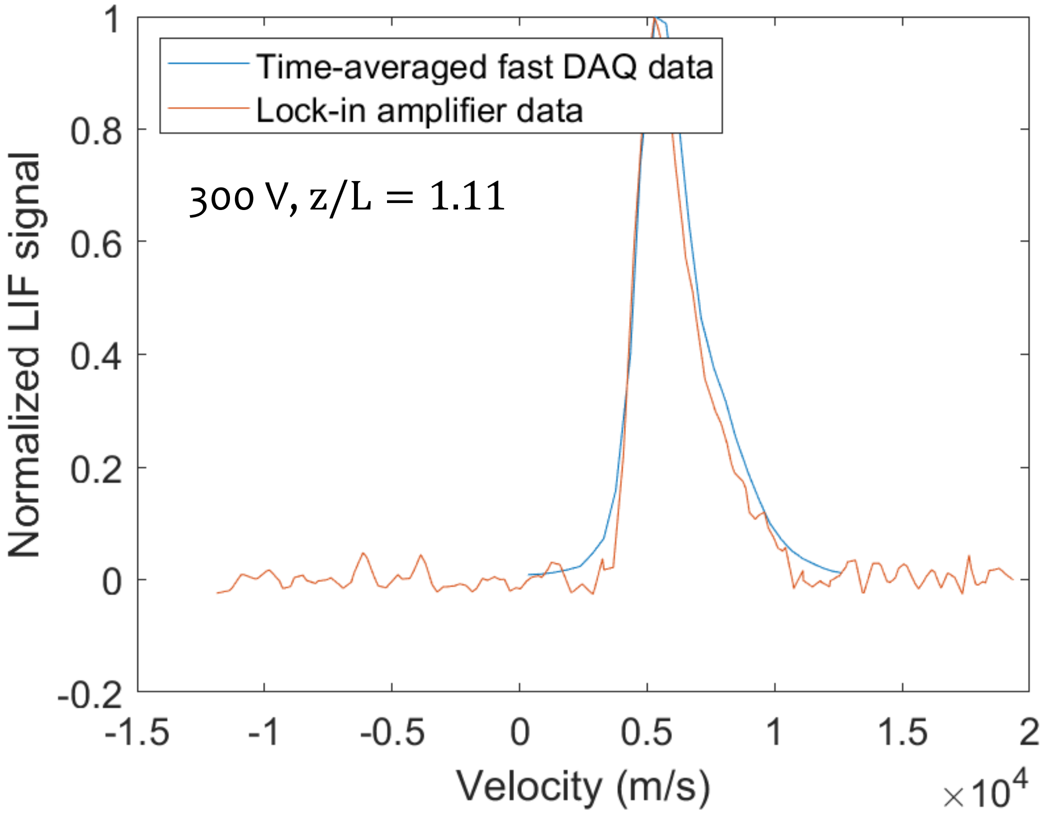
Aperiodic Oscillations – 300 V



Validation

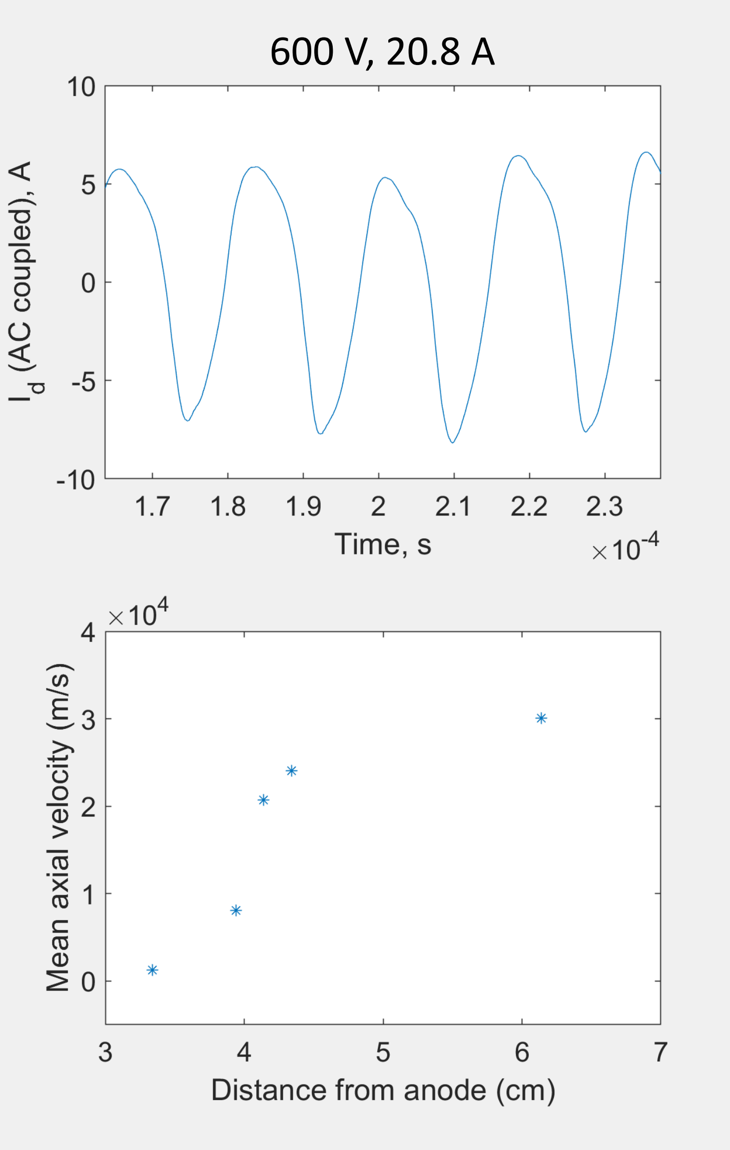


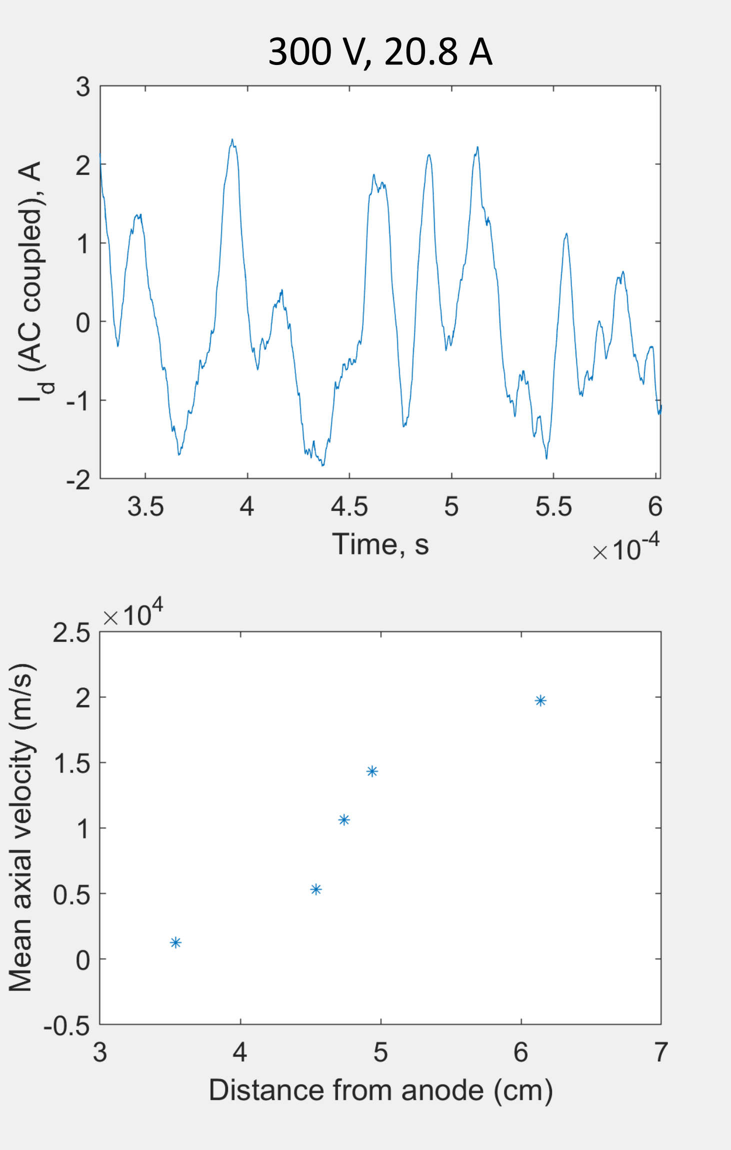
Time-averaged fast DAQ data
Lock-in amplifier data
600 V, z/L = 1.01
Normalized LIF signal
Velocity (m/s)
×10^4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.5
0
0.5
1
1.5
2
2.5
3



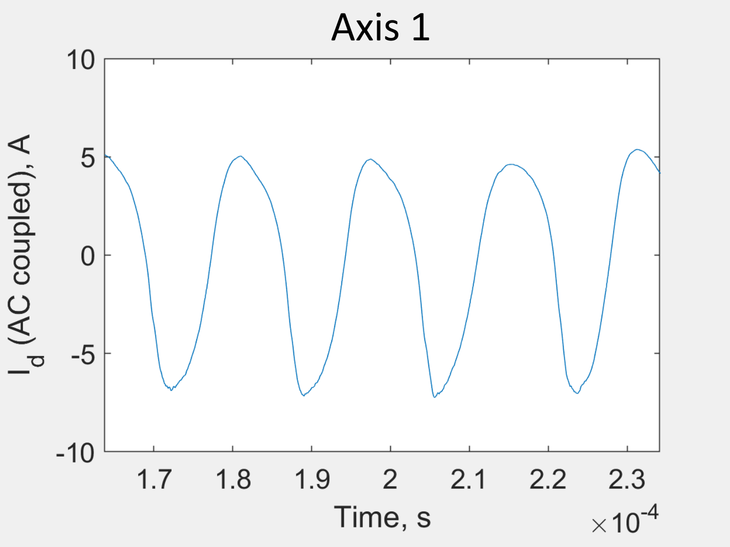
Time-averaged fast DAQ data
Lock-in amplifier data
300 V, z/L = 1.11
Normalized LIF signal
Velocity (m/s)
×10^4
1
0.8
0.6
0.4
0.2
0
-0.2
-1.5
-1
-0.5
0
0.5
1
1.5
2

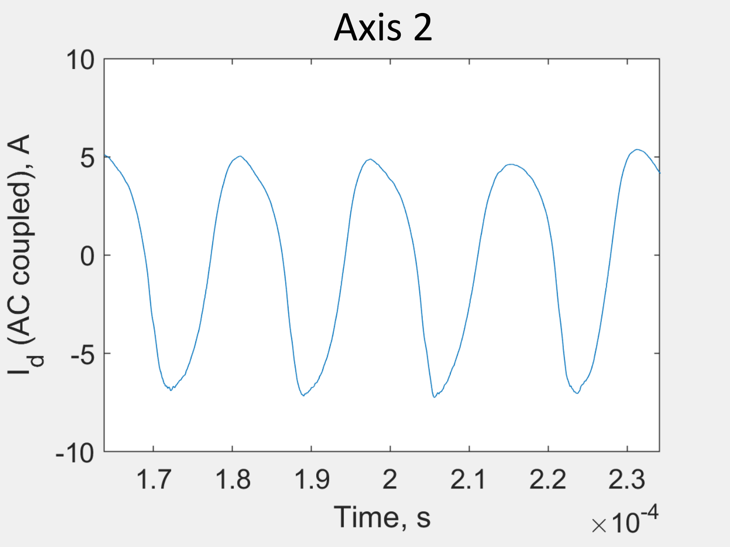
Mean Velocity Evolution

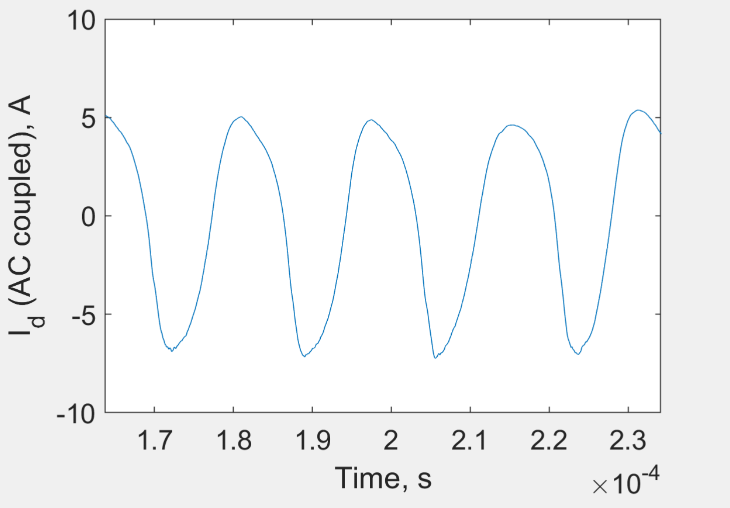


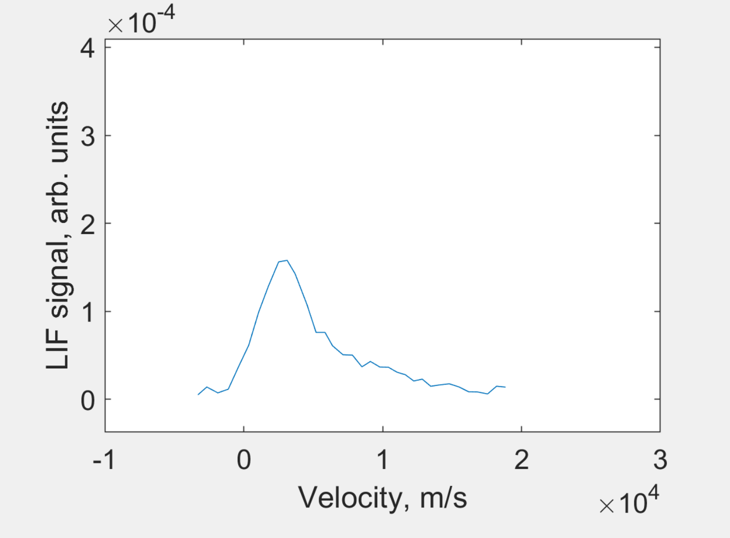


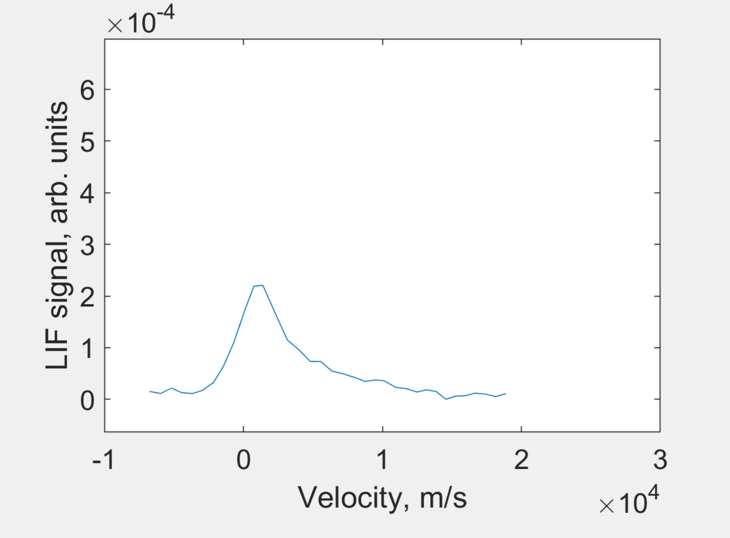
Off-Centerline – 600 V

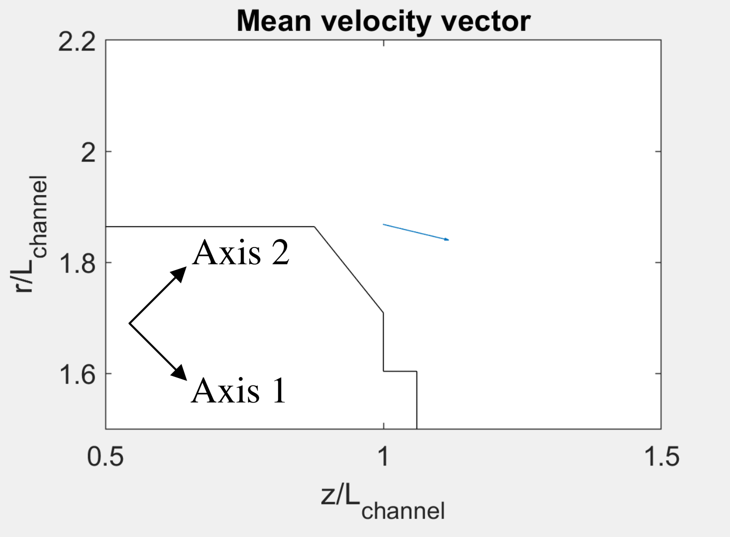




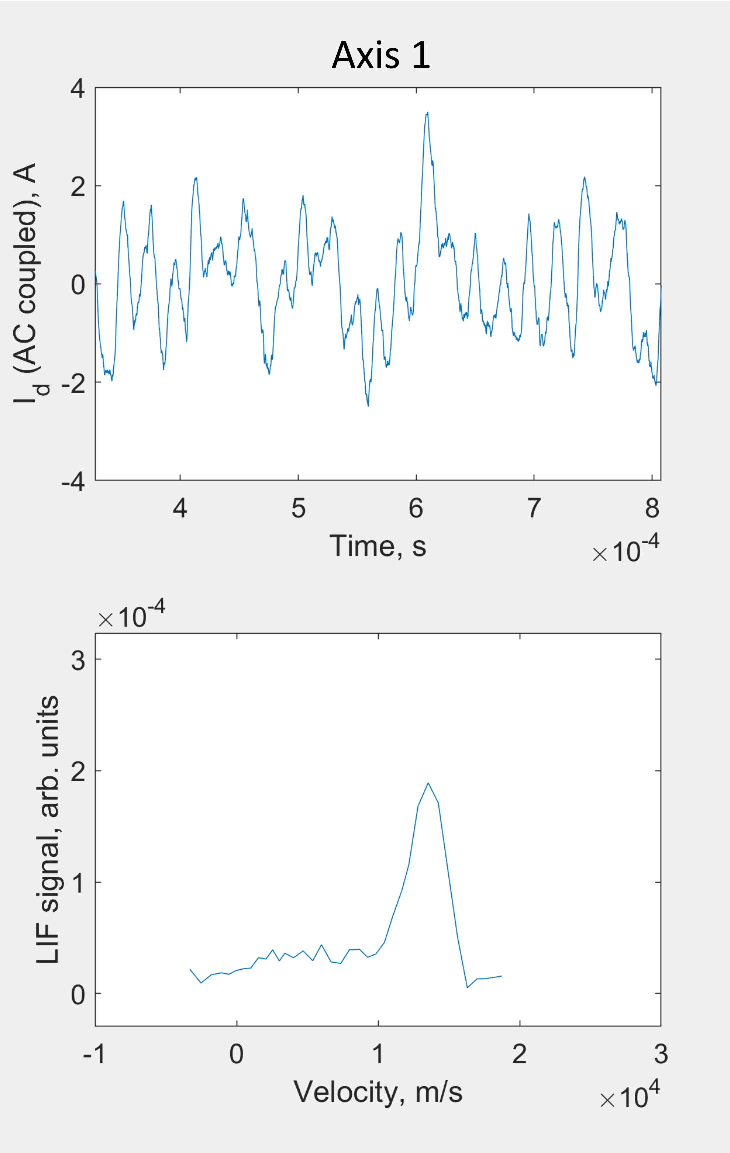


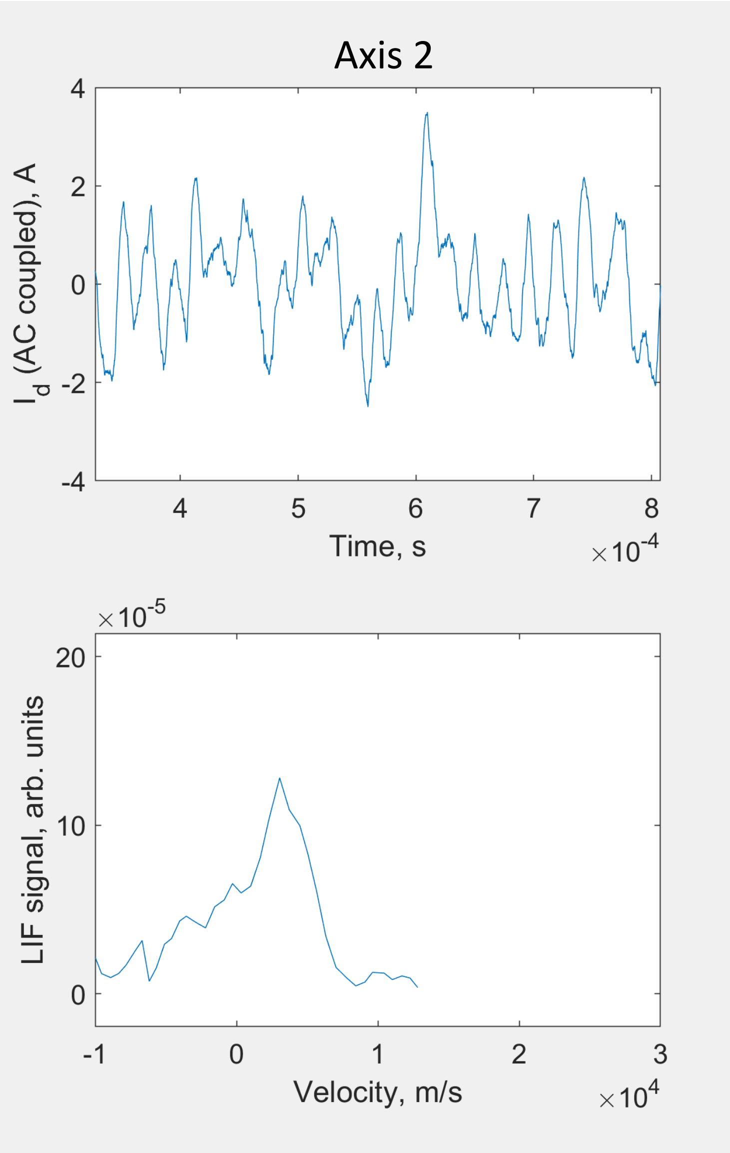


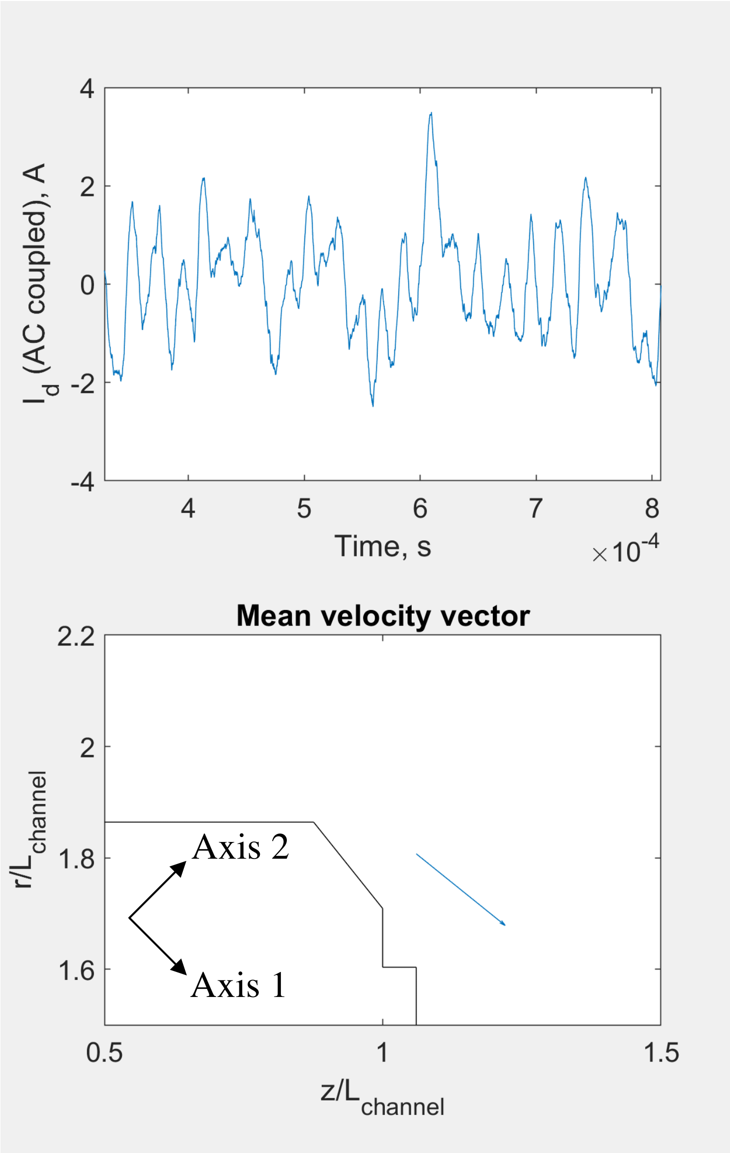




Off-Centerline – 300 V







Acknowledgements

- This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The support of the joint NASA GRC and JPL development of HERMeS by NASA's Space Technology Mission Directorate through the Solar Electric Propulsion Technology Demonstration Mission (SEP TDM) is gratefully acknowledged.
- The authors would also like to thank **Ray Swindlehurst** and **Nowell Niblett** for their assistance in setting up the LIF optics, installing the thruster for testing, and maintaining the vacuum facility.